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A high degree of direct torque control applied to a grid-connected wind energy system based on a DFIG

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Abstract

This paper presents the performances improvement of a doubly fed induction generator (DFIG) driven by a wind turbine (WT) using direct torque control (DTC). However, the major drawbacks related to DTC are high torque/flux ripples that produce mechanical vibration and disagreeable noise. The use of multilevel inverters seems to be an interesting solution. A three-level voltage source (inverter) converter (3LVSI) connected to the rotor side of the DFIG is considered in this paper. The high freedom degree of the voltage vectors selection in the 3LVSI allows a control with minimal torque and flux ripples. In addition, a fuzzy logic approach is introduced, to ensure an intelligent extraction of the energy sweeping the WT blades. A variable adjustment step enables an optimal extraction in a minimum tracking time with significant reduction of oscillations in the steady state. Simulation results obtained using MATLAB/SIMULINK demonstrate the effectiveness of the 3LVSI-DTC control based on Fuzzy MPPT in the wind energy conversion system (WECS).

Keywords: Doubly fed induction generator, Three-level voltage source inverter, Direct torque control, Fuzzy MPPT, Wind turbine

1. Introduction

The renewable energy production based wind energy has undergone considerable progress in the last few years. Indeed, the modes of production are based on the characteristics of wind turbines (WT) but essentially on the electrical generator and its control [1,2,3]. The doubly fed induction generator (DFIG) has become very popular in grid-connected wind power systems [4,5], because of the ability to control the DFIG in the rotor side. The DFIG can operate in a wide range of wind speeds. Since wind speed is random, the challenge of grid-connected wind turbines is to capture the maximum energy from the wind. Nevertheless, the power-velocity characteristic of the generator is bell-shaped and it is specific for each turbine. Several techniques have been proposed in this context [6]. The perturb and observe (P&O) technique is the best known. Its main principle is to propose reference speeds at fixed steps in order to get closer to the optimal speed. This technique can ensure maximum efficiency of the turbine. However, the performances achieved in [7] put this technique aside. In order to remedy this situation, our idea is to replace the fixed step by a floating step taking into account the fuzzy approach.

Direct torque control (DTC) strategy is one of the promising control strategies. It is known for its several advantages (ease of implementation, high dynamics, and robustness against parametric variations) [8,9]. However, this technique is subject to a lot of criticism because of the important torque and flux ripples that appear in the machine to be controlled that produce mechanical vibration and disagreeable acoustic noise. Control structures using multilevel inverters increase efficiency by optimizing switch losses [10,11,12]. The implementation of a three-level voltage source inverter (3LVSI) can greatly improve the performance due to the higher degree of freedom in the selection of the voltage vector.

This paper intended to improve the performance of the WT-DFIG connected to the grid. For this purpose, 3LVSI replaces the two-level voltage source inverter (2LVSI) for efficient DTC control on the DFIG. In addition, the contribution of fuzzy logic MPPT controller (FLC) is introduced for a better optimization of the WT power. A simulation under MATLAB/Simulink is performed to validate the suggested control.

2. Modelling of WT-DFIG

The role of the wind turbine is to recover the kinetic energy of the wind that sweeps the blades of the turbine. The mechanical power on the turbine shaft is given by the following relation.

$$P_t = \frac{1}{2}.C_p(\lambda,\beta).\rho.S.v_w^3 \tag{1}$$

Where ρ is the air density, S is the circular area swept by the turbine and v_w is the wind speed. C_p represents the power coefficient, it allows to estimate the energy extracted by the turbine compared to the extractable energy. It depends on the speed ratio λ and the blade pitch angle β. C_p presents maximum value of 0.5 for an optimum value λ_{opt} of 8.9 as shown in Fig.1 for the pitch angle (β=0), it is defined by:

$$C_p = 0.5.\sin(\pi(\lambda + 0.1)/18) \tag{2}$$

The wind turbine power characteristic curves versus speed ratio are represented in Fig.2 for different wind speeds, it has a parabolic form as presented in Fig. 2

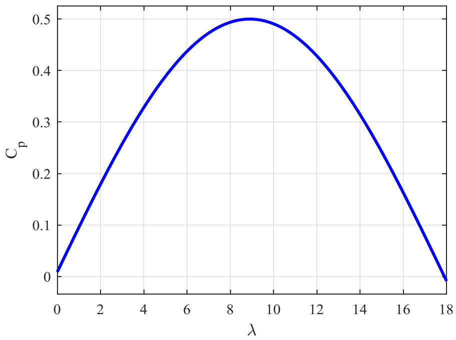

Fig 1. $C_p(\lambda,\beta)$ Characteristic for $\beta=0°$

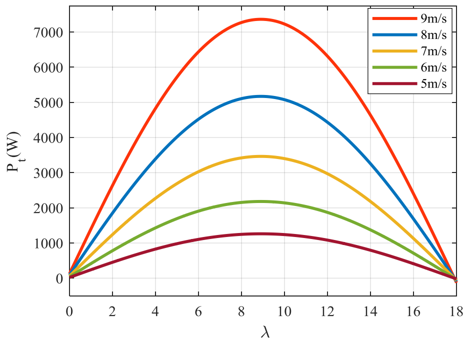

Fig 2. $P_t(\lambda)$ for different wind speeds

A gearbox is used to adjust the slow speed of the turbine Ω_t to the speed of the DFIG. It is represented by the following equations.

$$\begin{cases} T_m = \dfrac{T_t}{G} \\ \Omega_m = \Omega_t.G \end{cases} \tag{3}$$

The mechanical torque of the generator can be calculated from the following equation:

$$T_m = \frac{\pi}{2\lambda}.\frac{C_p(\lambda,\beta).\rho.R^3.v_w^3}{G} \tag{4}$$

The electrical model of the DFIG expressed in the d-q synchronous frame is given by the following equations.

$$\begin{cases} V_{sd} = R_s i_{sd} + \dfrac{d\psi_{sd}}{dt} - w_s \psi_{sq} \\ V_{sq} = R_s i_{sq} + \dfrac{d\psi_{sq}}{dt} + w_s \psi_{sd} \\ V_{rd} = R_r i_{rd} + \dfrac{d\psi_{rd}}{dt} - w_r \psi_{rq} \\ V_{rq} = R_r i_{rq} + \dfrac{d\psi_{rq}}{dt} + w_r \psi_{rd} \end{cases} \tag{5}$$

Where V_{sd}, V_{sq}, V_{rd} and V_{rq} are respectively stator and rotor voltage in the d-q frame; i_{sd}, i_{sq}, i_{rd} and i_{rq} are respectively stator and rotor current in the d-q frame; R_s and R_r are respectively stator and a rotor phase resistance; w_s and w_r are respectively stator and rotor currents pulsations.

The electromagnetic torque is expressed as a function of the rotor currents, the flux and the pair pole number P [6]:

$$T_{em} = P(\psi_{rd} i_{rq} - \psi_{rq} i_{rd}) \tag{6}$$

3. Maximum power point tracking (MPPT) based on fuzzy logic controller (FLC)

The FLC has the ability to deal with nonlinear system or complex mathematical models and the possibility of exploiting tolerance for some inexactness and imprecision [13,14,15]. Its contribution in the concept of MPPT is to follow the MPP quickly and accurately with a variable adjustment step as shown in fig. 3. In fig. 4, the numerical variables $(\Delta P_t, \Delta\Omega_t)$ will be replaced by variable linguistics at the output of a fuzzification block. The fuzzy variables are introduced in an inference table. The defuzzification block will convert the fuzzy reference into a real variable. The fuzzy reference is obtained from the fuzzy rules presented in Table 1.

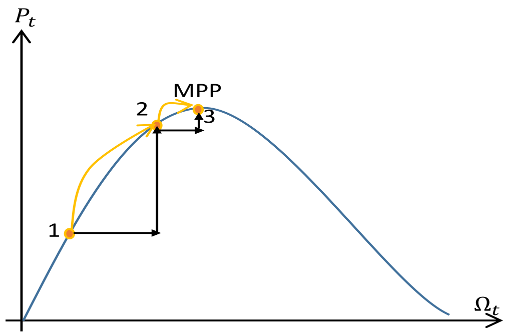

Fig 3. Maximum power searching using fuzzy MPPT technique

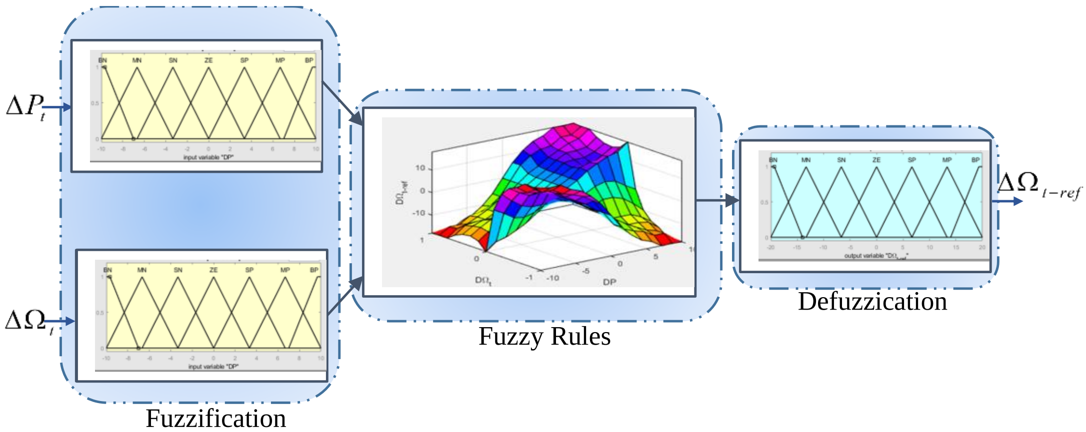

Fig 4. Fuzzy logic controller bloc

Table 1. Fuzzy MPPT controller rule table [16]

ΔP_t / $\Delta \Omega_t$	**BN**	**MN**	**SN**	**ZE**	**SP**	**MP**	**BP**
BN	BP	BP	MP	ZE	MN	BN	BN
MN	BP	MP	SP	ZE	SN	MN	BN
SN	MP	SP	SP	ZE	SN	SN	MN
ZE	BN	MN	SN	ZE	SP	MP	BP
SP	MN	SN	SN	ZE	SP	MP	MP
MP	BN	MN	SN	ZE	SP	MP	BP
BP	BN	BN	MN	ZE	MP	BP	BP

Figs (5, 6) show the obtained results of the FLC technique compared to the P&O method, which show fast response and contrariwise of P&O technique the oscillation around maximum wind power point has been significantly reduced close to zero using the proposed fuzzy MPPT technique.

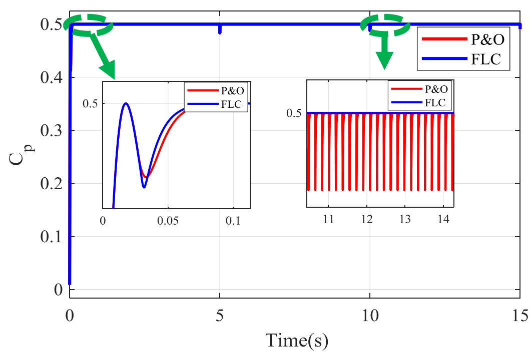

Fig 5. Power coefficient waveform.

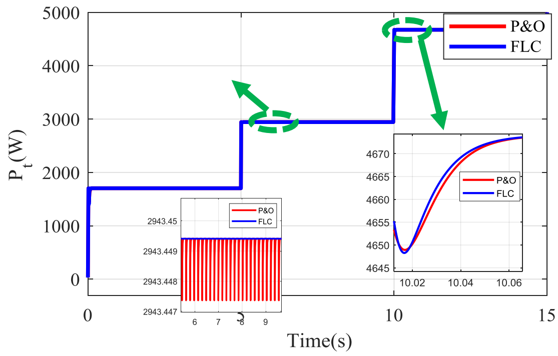

Fig 6. Wind Turbine power waveform

4. Direct torque control of DFIG

Unlike the vector oriented control (VOC), the DTC control directly selects the appropriate voltage vectors to regulate the torque and flux. The selection of the voltage vectors is performed using a switching table in order to correct the error levels given by the two hysteresis controllers. In order to determine the right voltage vector, the position of the rotor flux is necessary.

The rotor flux magnitude can be estimated by the following two equations.

$$\begin{cases} \psi_{r\alpha}(t) = \int_0^t (V_{r\alpha} - R_r i_{r\alpha})dt \\ \psi_{r\beta}(t) = \int_0^t (V_{r\beta} - R_r i_{r\beta})dt \end{cases} \tag{7}$$

$$\psi_r = \sqrt{\psi_{r\alpha}^{\ 2} + \psi_{r\beta}^{\ 2}} \tag{8}$$

The position of the rotor flux is given by the next equation.

$$\theta = \tan^{-1}\frac{\psi_{r\beta}}{\psi_{r\alpha}} \tag{9}$$

The expression of the electromagnetic torque is given by equation 10.

$$T_{em} = P(\psi_{r\alpha} i_{r\beta} - \psi_{r\beta} i_{r\alpha}) \tag{10}$$

The power converter is an important part in the DTC control. The torque and flux hysteresis controllers' levels depend mainly on the choice of voltage vectors. In contrast to the two-levels converter, the three-levels converter offers the possibility of minimizing torque and flux ripples due to the large degree of freedom in the choice of voltage vectors, as shown in the following figure.

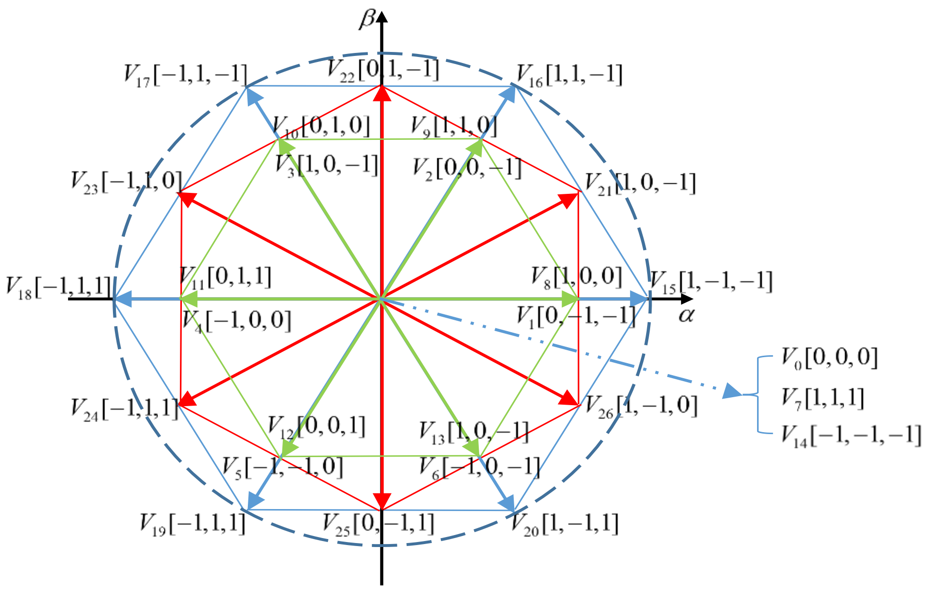

Fig 7. Voltage vectors provided by the three-level inverter

The electromagnetic torque error and the rotor flux error are modulated respectively by a five-level and three-level hysteresis comparators. The decision for the selection of the appropriate vector is based on the rotor flux position in the twelve sectors. The overall scheme of the WT-DFIG control by 3LVSI-DTC is shown in Fig. 8. The selection of the voltage vectors is illustrated in Table 2.

Table 2. Three-level inverter DTC switching table [10].

H_φ	H_{Tem}	Sectors											
		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}
+1	+2	V_{21}	V_{16}	V_{22}	V_{17}	V_{23}	V_{18}	V_{24}	V_{19}	V_{25}	V_{20}	V_{26}	V_{15}
	+1	V_{21}	V_2	V_{22}	V_3	V_{23}	V_4	V_{24}	V_5	V_{25}	V_6	V_{26}	V_1
	0	Zero vector											
	-1	V_{26}	V_1	V_{21}	V_2	V_{22}	V_3	V_{23}	V_4	V_{24}	V_5	V_{25}	V_6
	-2	V_{26}	V_{15}	V_{21}	V_{16}	V_{22}	V_{17}	V_{23}	V_{18}	V_{24}	V_{19}	V_{25}	V_{20}
0	+2	V_{22}	V_{17}	V_{23}	V_{18}	V_{24}	V_{19}	V_{25}	V_{20}	V_{26}	V_{15}	V_{21}	V_{16}
	+1	V_{22}	V_3	V_{23}	V_4	V_{24}	V_5	V_{25}	V_6	V_{26}	V_1	V_{21}	V_2
	0	Zero vector											
	-1	V_{25}	V_6	V_{26}	V_1	V_{21}	V_2	V_{22}	V_3	V_{23}	V_4	V_{24}	V_5
	-2	V_{25}	V_{20}	V_{26}	V_{15}	V_{21}	V_{16}	V_{22}	V_{17}	V_{23}	V_{18}	V_{24}	V_{19}
-1	+2	V_{17}	V_{23}	V_{18}	V_{24}	V_{19}	V_{25}	V_{20}	V_{26}	V_{15}	V_{21}	V_{16}	V_{22}
	+1	V_3	V_{23}	V_4	V_{24}	V_5	V_{25}	V_6	V_{26}	V_1	V_{21}	V_2	V_{22}
	0	Zero vector											
	-1	V_5	V_{25}	V_6	V_{26}	V_1	V_{21}	V_2	V_{22}	V_3	V_{23}	V_4	V_{24}
	-2	V_{19}	V_{25}	V_{20}	V_{26}	V_{15}	V_{21}	V_{16}	V_{22}	V_{17}	V_{23}	V_{18}	V_{24}

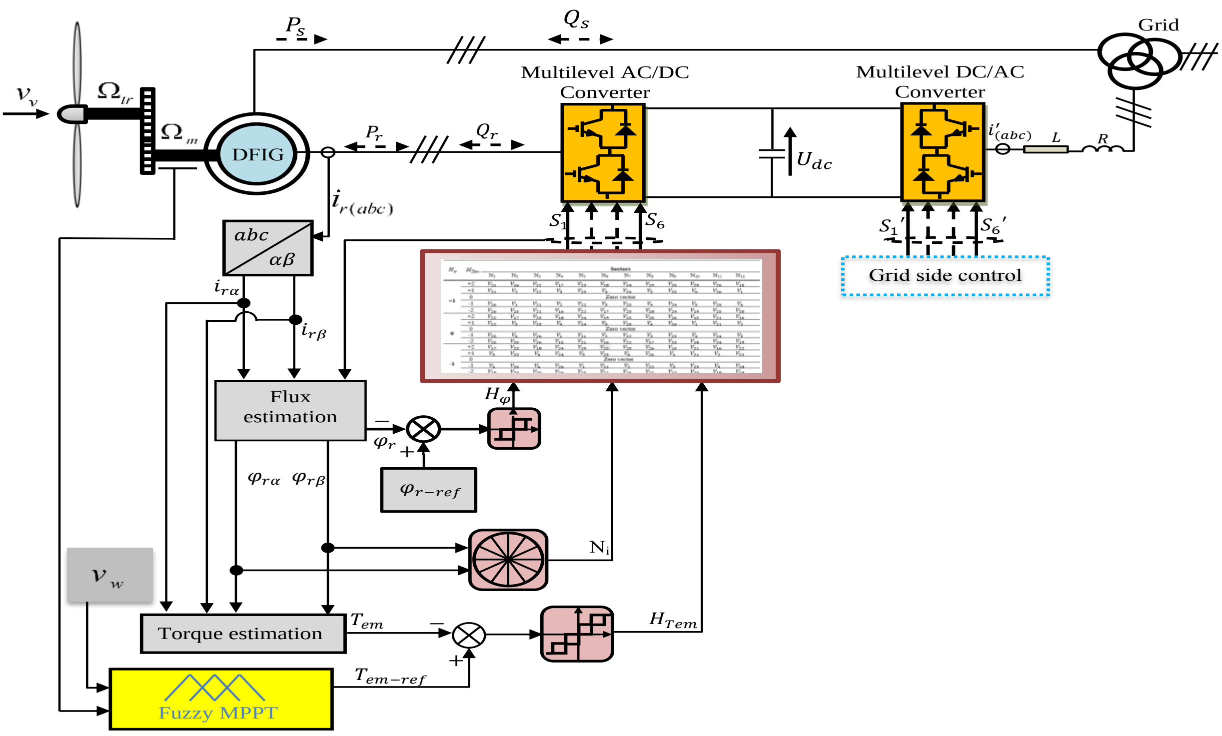

Fig 8. Block diagram of WT-DFIG control by 3LVSI-DTC based on fuzzy MPPT.

5. Results and discussion

The proposed control is evaluated by simulation under MATLAB/ Simulink for a WT- DFIG power of 7.5kW. The simulation was performed using variable wind speed in order to operate the DFIG in the three operation modes (sub synchronous, super synchronous and synchronous modes).

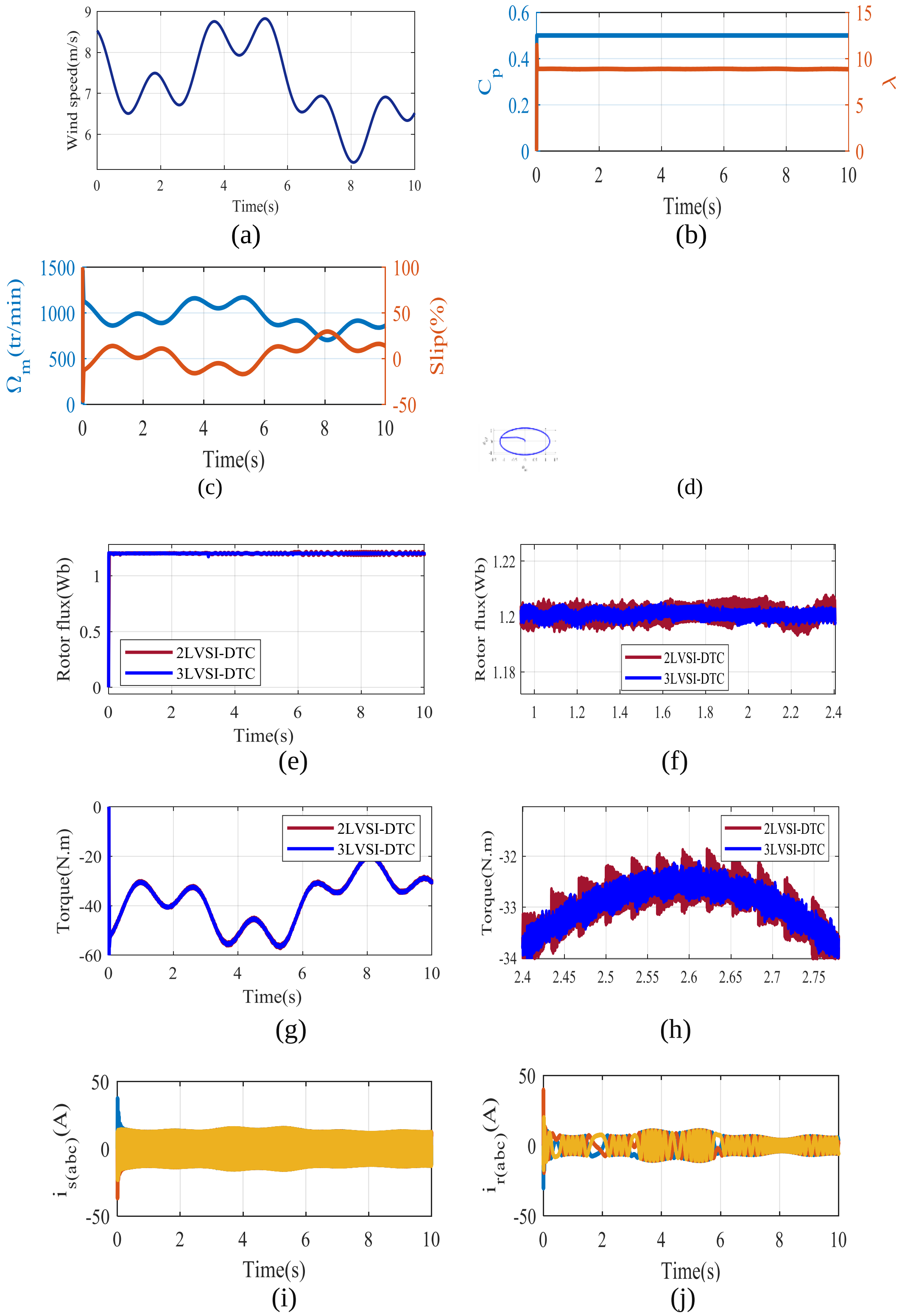

Fig 9. Simulation results of the proposed control, (a) Wind speed profil, Rotor flux, (b) Aerodynamic efficiency and speed ratio, (c) Rotational speed and slip,(d)(e) Rotor flux, (f) zoom of rotor flux, (g) Torque, (h) zoom of torque, (i) Stator current waveform, (j) rotor current waveform.

Figure.9 presents the simulation results of WT-DFIG with the 3LVSI-DTC. The DFIG operates in all three modes of operation without exceeding $\pm 30\%$ slip. In super-synchronous mode, the DFIG sends energy back to the grid via the stator and the rotor. When operating in synchronous mode, the rotor current is constant, the active power exchange between the grid and the rotor is cancelled as shown in fig .10. The evolution of the electromagnetic torque and the rotor flux under a random wind profile obtained with the 2LVSI-DTC and 3LVSI-DTC control have been presented in fig.9 (d-h). The rotor flux follows its reference value of 1.2Wb. The electromagnetic torque tracks the evolution of the reference torque obtained after fuzzy MPPT optimization.

The effectiveness of the proposed control can be seen by zooming in on the rotor flux and the electromagnetic torque (fig. 9 (f, h). A significant decrease in torque and flux ripples were observed with the 3LVSI-DTC control compared to the 2LVSI-DTC control results. This explains the considerable improvement in the quality of the stator current returned to the grid (fig .11).

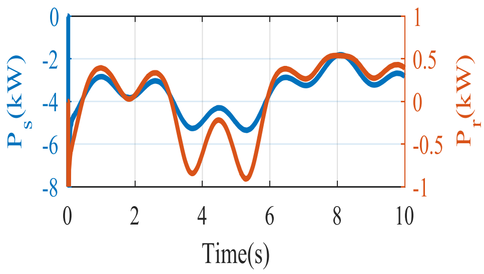

Fig 10. Waveforms of the stator and rotor active power.

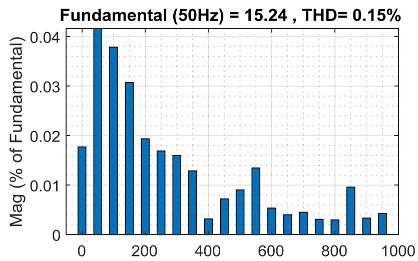

Fig 11. Harmonic spectrum of the stator current obtained with 3LVSI-DTC

6. Conclusion

Robust control and fuzzy optimization of wind energy conversion system based on DFIG is proposed in this work. The fuzzy logic MPPT technique ensures fine and fast power tracking whatever the wind speed variation. The simulation results, obtained with 3LVSI-DTC based on the Fuzzy MPPT were compared with those achieved with the conventional 2LVSI-DTC, and show fast response, weak ripples of torque and flux due to the higher degree of freedom in the selection of the voltage vector and low total harmonic distortion. Control structures using multilevel inverters increase the efficiency by optimizing the switching losses.

7. References

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